Direct Interpretation of COSMIC Refractivity Data in the Tropical Cyclone Environment

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Introduction

The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) is capable of accurately measuring water vapor in remote regions of the atmosphere (Anthes et al. 2008). Six microsatellites in COSMIC measure the vertical profile of refractivity (N) of Global Positioning System (GPS) radio signals through the atmosphere. A vertical profile of moisture from COSMIC can be resolved to 100 m of depth, with negligible interference from clouds and precipitation.

As first shown by Smith and Weintraub (1953), radio signal refractivity is related to temperature (T), pressure (p), and vapor pressure (e) by the expression:

$$N = 77.6\frac{p}{T} + 3.73\times10^{5}\frac{e}{T^{2}}$$

Assuming negligible errors with N and p, Ware et al. (1996) shows that the error range of vapor pressure, Δe, can be provided in terms of ΔT as:

$$\Delta e \approx \frac{2TN - 77.6p}{3.73\times10^{5}}\Delta T$$

In the tropical environment, both T and N are higher in value and act to increase Δe. However, T is typically observed to be steady over the tropical oceans, making ΔT low, which acts to reduce Δe. Therefore, if only N varies, then a useful measure of moisture (e) is obtained from N in the tropical maritime environment.

Relation of GPS Refractivity to Tropospheric Thermodynamics

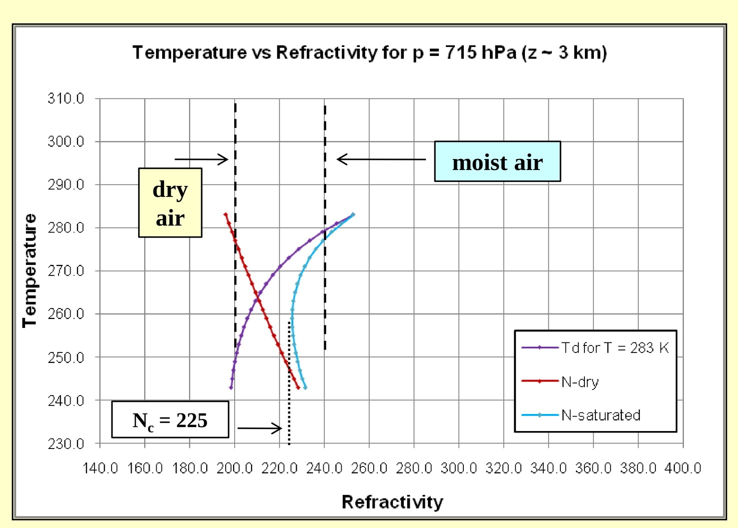
The relation from Smith and Weintraub can be modified to provide a "saturated N", in which $e = e_s$. Since e_s is a function of T, there exists an upper limit of N (or N_s) for given values of p and T. Likewise, with $e = 0$, a lower limit of N (or N_d) is obtained for p and T. Provided that ΔT is small, the range of possible $N(p)$ corresponds to a range of RH.

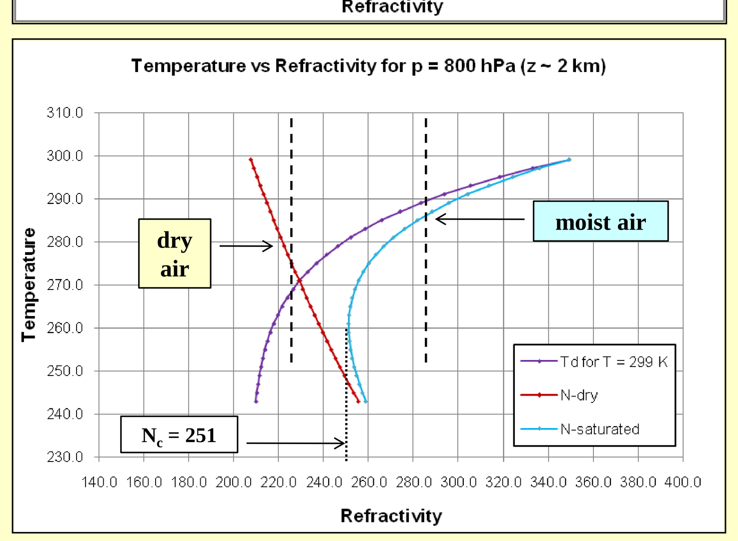
$$N_d = 77.6\frac{p}{T}$$

$$N - N_d = 3.73\times10^{5}\frac{e}{T^{2}}$$

$$N_s - N_d = 3.73\times10^{5}\frac{e_s}{T^{2}}$$

$$\frac{N - N_d}{N_s - N_d} = \frac{e}{e_s} = RH$$





Both for increasing p and increasing T, the range of possible N likewise increases, making the measure of e (or RH) less sensitive to the measure of N. A high (low) value of N corresponds to a high (low)value of e.

Note that the $N_s(p,T)$ profile has a critical lower limit, $N_c(p)$, below which the air will not be saturated for any value of T.

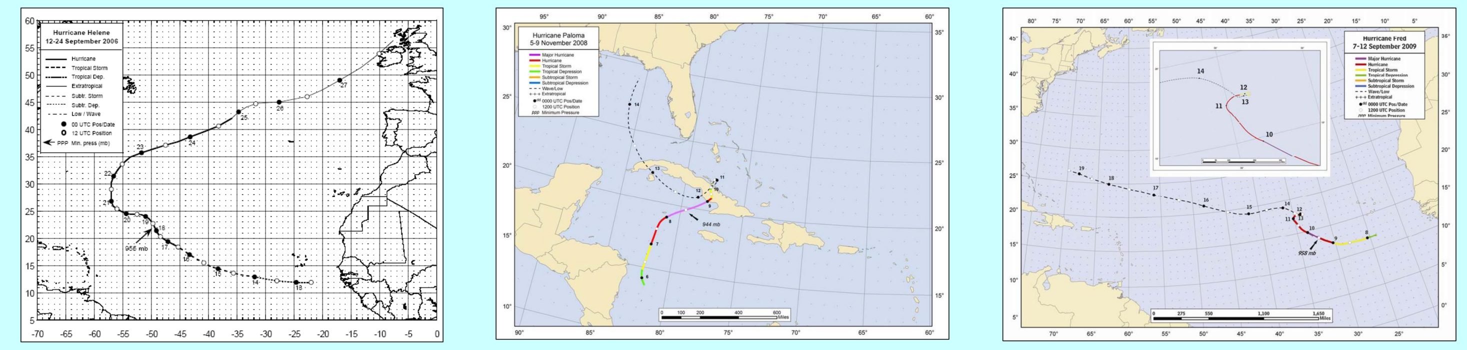
When substituting e for e_s in the equation of $N_s - N_d$, the term of temperature becomes the dewpoint temperature, T_d.

$$N_s - N_d = 3.73\times10^{5}\frac{e}{T_d^{2}}$$

If the observed value of $N(p)$ is equal to a hypothetical value of $N_s(p)$, then a minimum value of T_d at p is known. The presence of deep moist air with high values of T_d is necessary for the development and sustenance of tropical cyclones. Therefore, the direct measure of N from COSMIC can be used to diagnose the magnitude and depth of moisture in the tropical cyclone environment.

Methodology

The findings from the refractivity relation are applied to 1) the observed profiles of GPS refractivity near Hurricane Helene (2006), Hurricane Paloma (2008), and Hurricane Fred (2009), and 2) the summertime climatology of GPS refractivity for a wide area of the central and eastern Atlantic Ocean, including the main development region (MDR).

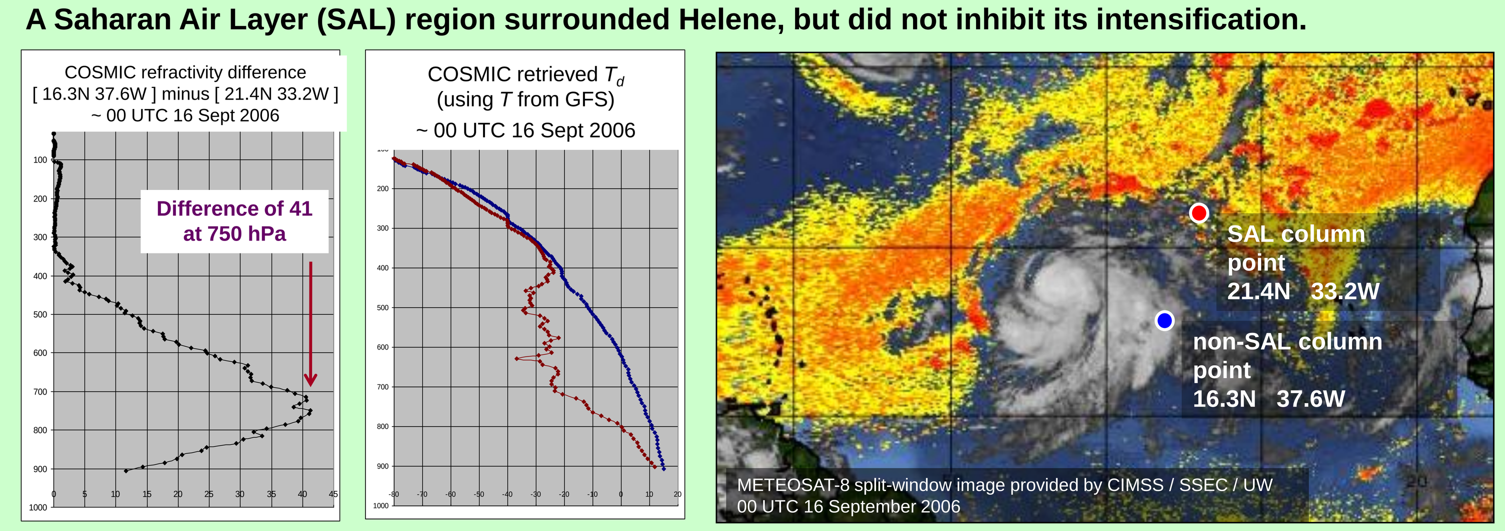


Best track position maps prepared by the National Hurricane Center.

Nomograms are created using an iterative routine to relate $N(p)$ values directly with T_d values. Height values from COSMIC observations are converted to pressure using a third-order polynomial that is based on the Jordan mean tropical soundings for June-September.

Helene 2006

A Saharan Air Layer (SAL) region surrounded Helene, but did not inhibit its intensification.

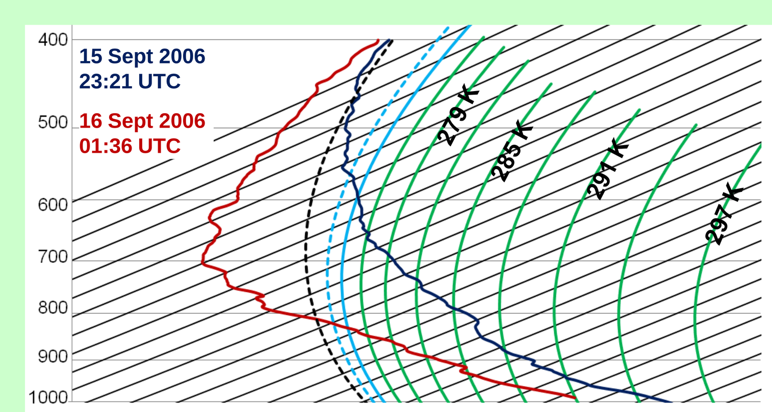


LEFT and CENTER: Profiles of differenced refractivity, and profiles of GFS-based T_d, from apparent SAL and non-SAL air columns near Helene. RIGHT: A difference of 12.0-μm and 10.8-μm wavelength brightness temperatures from METEOSAT-8 assists in the identification of the SAL and non-SAL regions.

When depicted on the nomogram, the COSMIC profiles of N reflect the vertical distribution of moisture in the SAL and non-SAL profile locations.

Compared with the GFS retrieval, the T_d = 273 K levels are correctly identified as ~ 800 hPa (600 hPa) in the SAL (non-SAL) profile.

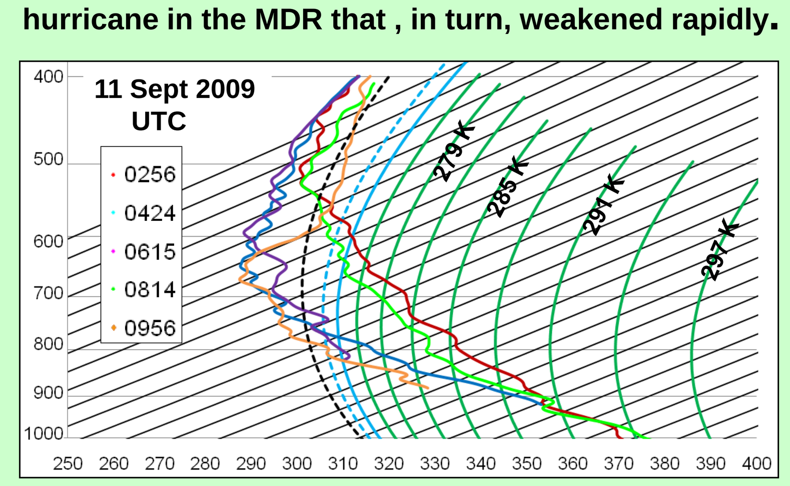
More detail is retained with the direct N values compared with the retrievals.

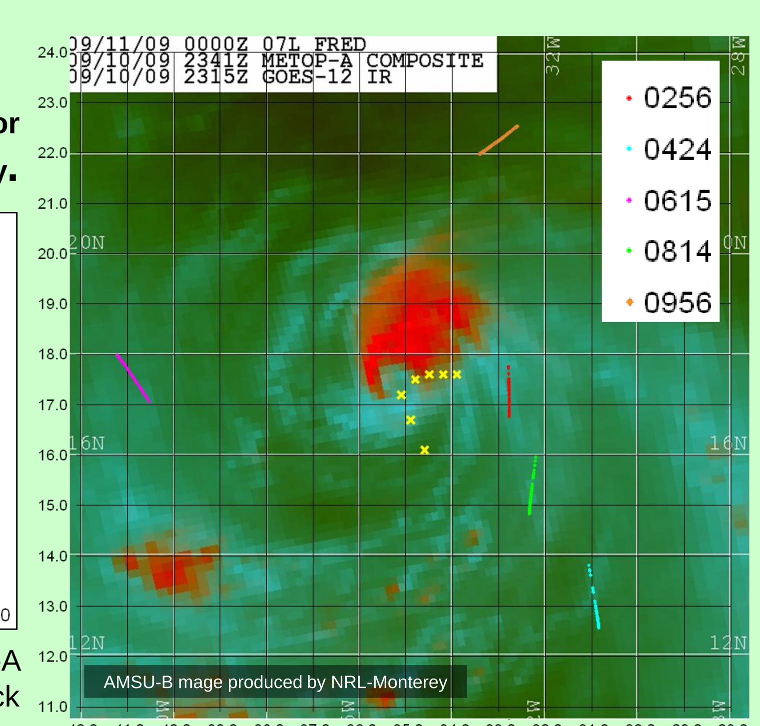


ABOVE: "Skew-N" nomogram, with profiles of refractivity vs. pressure. Green curves indicate T_d > 273 K, every 3 K. Blue solid curve is T_d = 273 K. Blue dashed curve is T_d = 270 K. Black dashed curve is N_c.

Fred 2009

An unusually southeasterly developed major hurricane in the MDR that , in turn, weakened rapidly.



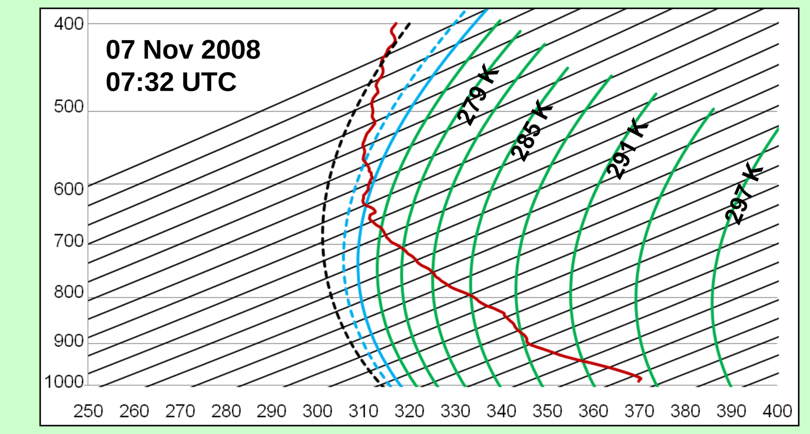


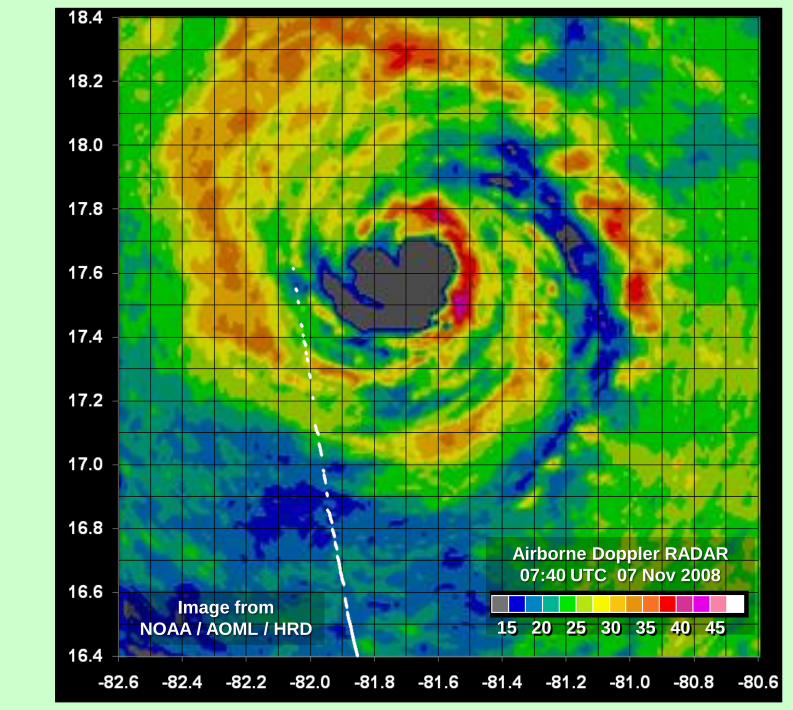
ABOVE: "Skew-N" nomogram. RIGHT: METEOP-A AMSU-B 89-/150-GHz image with NHC best track positions and COSMIC profile positions.

Three COSMIC profiles reflect low T_d values above 850 hPa around the periphery of Fred, indicating dry air and suppressed moist convection. To the north of Fred, relatively dry air appears to be confined to a layer of 600 – 850 hPa. Two other profiles depict greater moisture content and depth along a spiral band.

Paloma 2008

A COSMIC profile transected the inner core during RI and during a sampling of the cyclone by airbone Doppler radar.



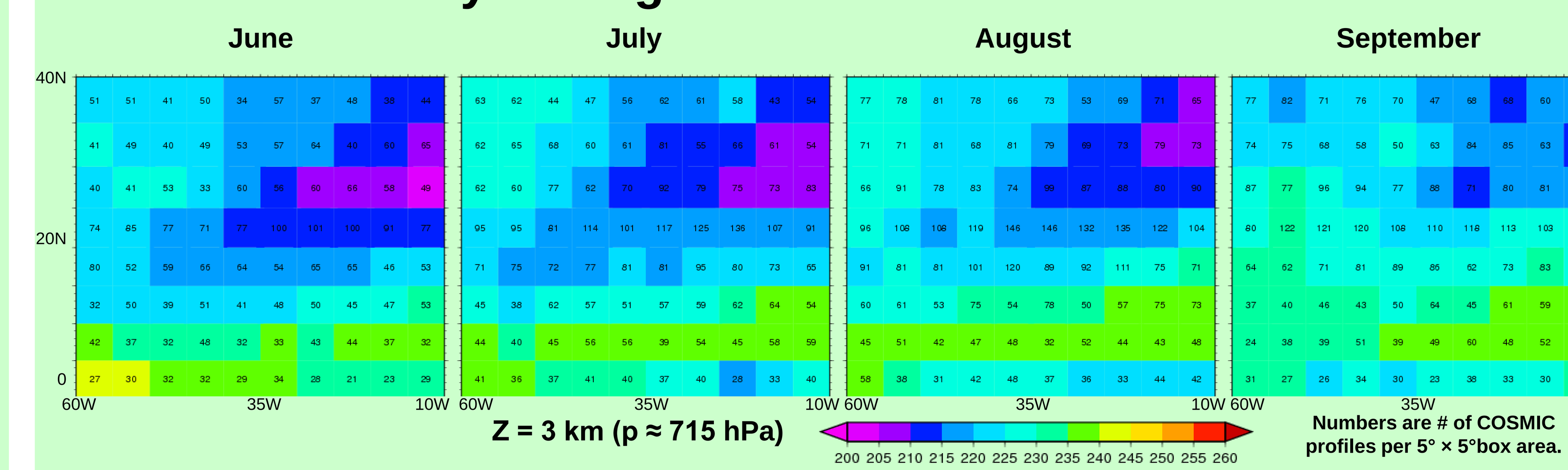


ABOVE: "Skew-N" nomogram. RIGHT: Airborne Doppler radar image with COSMIC profile position.

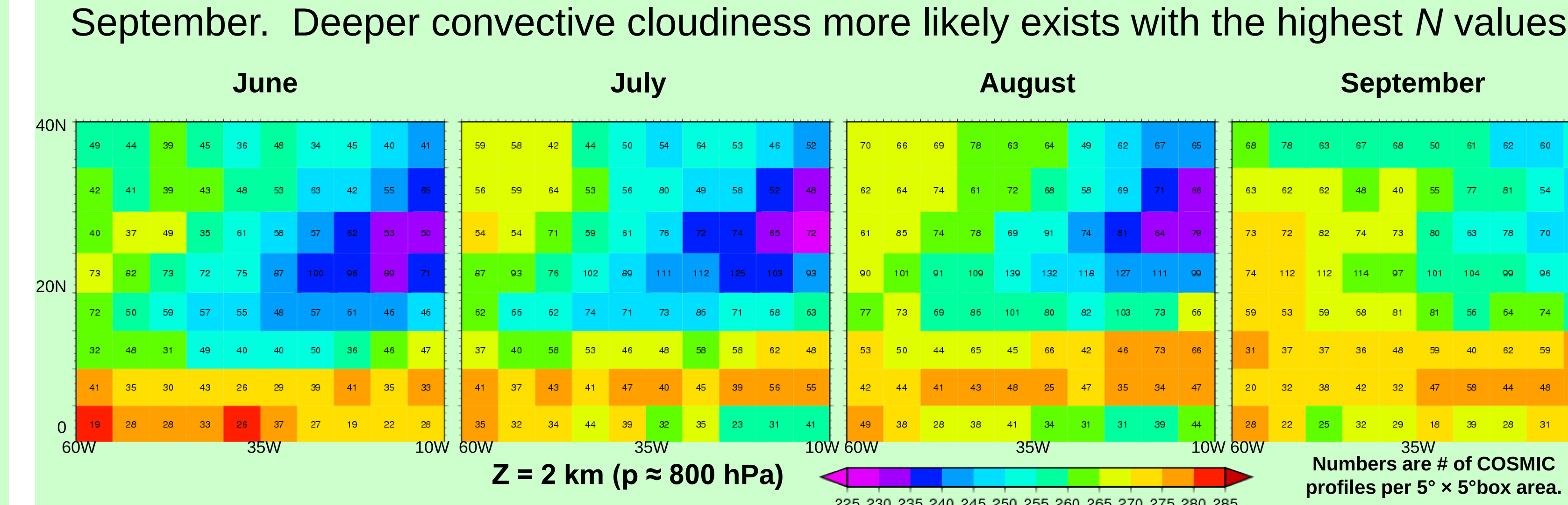
The available COSMIC profile, which increases in height with increasing distance from the center, reflects relatively high T_d values over a deep layer, including outside of convective precipitation areas.

A dropsonde profile (not shown) measured ~ 1 ½ hours earlier, and near the NE spiral band, indicated T_d = 288 K at 850 hPa and T_d = 273 K at 605 hPa, similar to the COSMIC profile.

2006-2009 Monthly averages of COSMIC-observed GPS refractivity



With N_c = 225, the air in the study region at z = 3 km is normally unsaturated north of 10°N in June. The presence of moisture increases northward and eastward from July to September. Deeper convective cloudiness more likely exists with the highest N values.



Based on average N, there exists a significant contrast of moisture at z = 2 km along 10°N in June and along 15°N in July. This contrast becomes more diffuse through August and September, with increased moisture and cloudiness throughout the study area. N at this level may serve as a better indicator for probable convection.

Conclusions

- Though sporadic in space and time, COSMIC observations of GPS refractivity can provide moisture profile information where reconnaissance flight data and other satellite data are not available – useful for observing the environment of remote tropical cyclones
- Analyses of direct GPS refractivity observations compare well with existing means of analyzing moisture distribution
- From the examples provided here, low (high) refractivity at 2 km is indicative of a dry (moist) profile over the tropical Atlantic Ocean
- Future work: expand study throughout the Atlantic Ocean basin

References

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Ware, R., M. Exner, D. Feng, M. Gorbunov, K. Hardy, B. Herman, Y.-H. Kuo, and others, 1996: GPS sounding of the atmosphere from low Earth orbit: preliminary results. *Bull. Amer. Meteor. Soc.*, **77**, 19-40.